Project title: An Integrated Framework for Controlled Mobility in Ad-hoc Networks

Principal Investigator: Eric W. Frew
Co-investigator: Timothy Brown
Institution: University of Colorado
Grant Number: FA9550-06-1-0205

Final Report
July 9, 2009

20120918153

2. Objectives:

The overall goal of the research proposed here is to develop a framework for controlled mobility in ad-hoc networks that integrates data ferrying in sparse or delay tolerant networks with local decentralized control for improved real-time network flow. Specific objectives to be completed as part of this work include:

O1. **Define Performance Metrics:** Investigate metrics for understanding the effects of controlled mobility on ad-hoc networks. These metrics will be functions of network objectives such as packet delay and throughput; mobile node capabilities such as speed and buffer size; and client node behavior such as speed and spatial density.

O2. **Design Ferry-Based Communication Algorithms:** Develop and evaluate controlled mobility algorithms for data ferries in sparse or delay tolerant networks. Multiple mobility control algorithms will be designed and evaluated against the metrics defined in O1. Algorithms will be identified that have superior performance in different scenarios.

O3. **Integrate Realistic Communication Models:** Design feedback controllers and transmission protocols that optimize data ferrying given a continuous model of communication rate versus separation distance. Standard wireless communication models use the simple assumption that communication is constant up until some specified separation distance. In reality wireless communication channels are richer than this, with the channel capacity set based on the ratio of measured signal to noise power.

O4. **Develop Ferry Allocation Algorithms:** Develop linear programming and reinforcement learning techniques for optimal allocation of data ferries in multicast networks. Unknown motion of task nodes in an ad-hoc network will be addressed by the development of reinforcement learning algorithms that adapt the data ferrying trajectories as the network evolves.

O5. **Decentralized Cooperative Control for Communication:** Analyze decentralized mobility control algorithms to improve the performance of real-time traffic flow through multi-hop links in the presence of unmodeled interference. Real-time data relaying will be recast as a decentralized control problem in which node mobility is directly tied to network performance metrics such as capacity.

O6. **Decentralized Cooperative Control for Other Tasks:** Evaluate distributed multi-objective control algorithms for networks of mobile nodes capable of carrying out primary tasks such as surveillance while also acting as data relays in an ad-hoc network. The decentralized control algorithms developed in O5 will be augmented to include additional objectives.

O7. **Demonstrate Integrated Concept:** Demonstrate the integration of data ferrying (developed in O2-O4) with decentralized mobility control for real-time flow (O5-06) in a single controlled mobility framework based on reinforcement learning and local, decentralized control. Simulations, laboratory experiments, and field deployments on the Ad-hoc UAV Ground Network (AUGNet) at CU Boulder will verify the concepts proposed here.

3. Status of Effort:

We completed objectives O1 – O5. Objective O6 was not achieved. Flight testing for objective O7 partially demonstrated O1-O5.

4. Major accomplishments:

1. The notion of a quality of service phase space (Fig. 1) was developed to show what communication modes (Direct, Relay, or Ferry) can provide a given QoS demand in terms of insertion delay and average throughput [C.18, J.3].

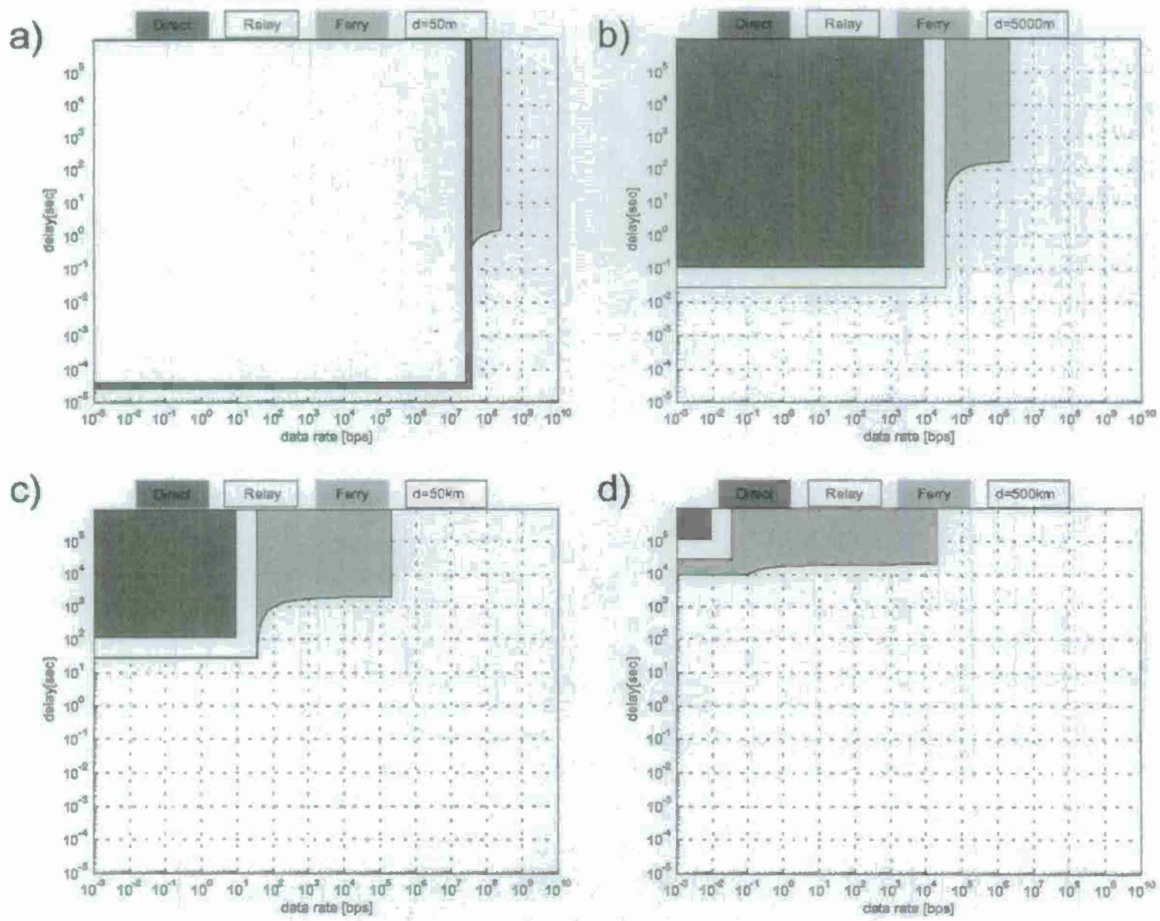

Figure 1. Phase space showing best communication modes for three-node network with source and destination nodes separated by a.) 50 m; b.) 5000 m; c.) 50 km; and d.) 500 km.

2. It was shown that a mobile node can be controlled to find the optimal relay point in a chain of relays using only local information (Fig. 2). The decentralized controller allows the network to self organize, self adapt when relays fail or noise sources are introduced, and tether to moving source/destination nodes. The underlying control theory has been developed and we are able to show stability of the decentralized system given several different link and network models [C.2, J.5].

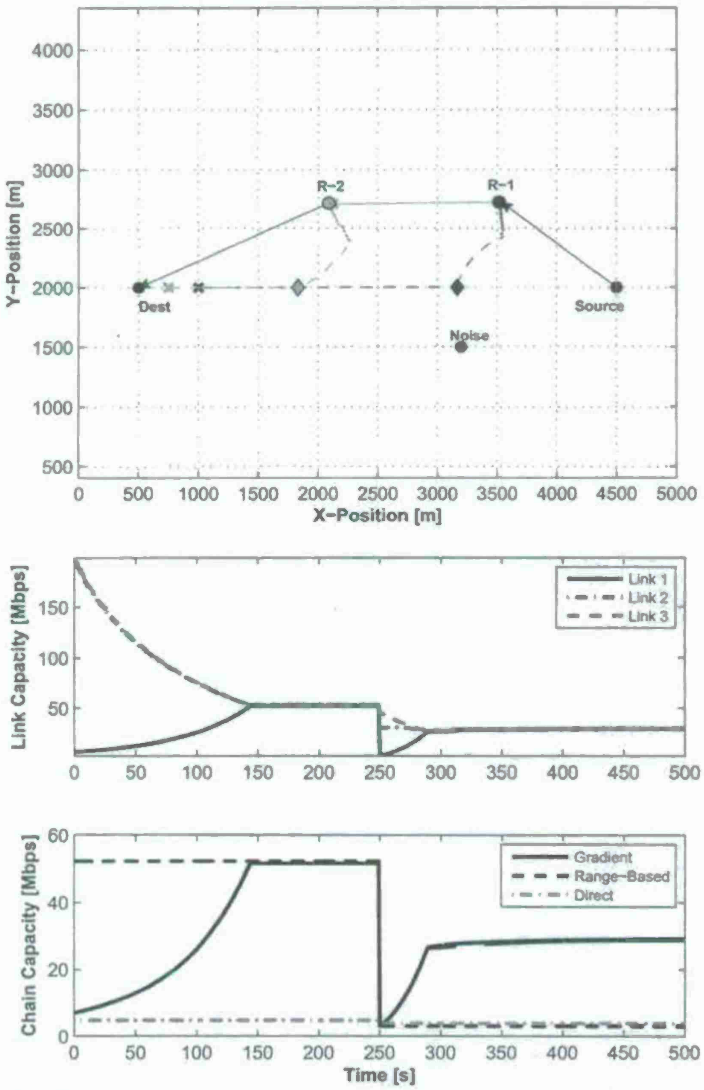

Figure 2. Simulation of a planar cascaded relay network using two point-mass robotic relay nodes in a flow-pipe network using the Shannon channel capacity model. At time t = 250 s a jamming noise source is introduced showing the ability of the gradient controller to react to changes in the RF environment and improve the capacity above that of a range-based solution. (a) Node positions in the environment and the path of the relays. The diamond markers represent the location of the range-based solution. (b) Capacity of the chain using the gradient controller compared to that obtained from a range-based solution, along with the direct link capacity. Note that the range-based solution has a lower capacity than using direct communication from the source to the destination.

3. An extremum seeking control architecture for electronic leashing and chaining applications was developed that combines vector field guidance, stochastic approximation, and gradient descent [J.1, T.1, C.2, J.6].

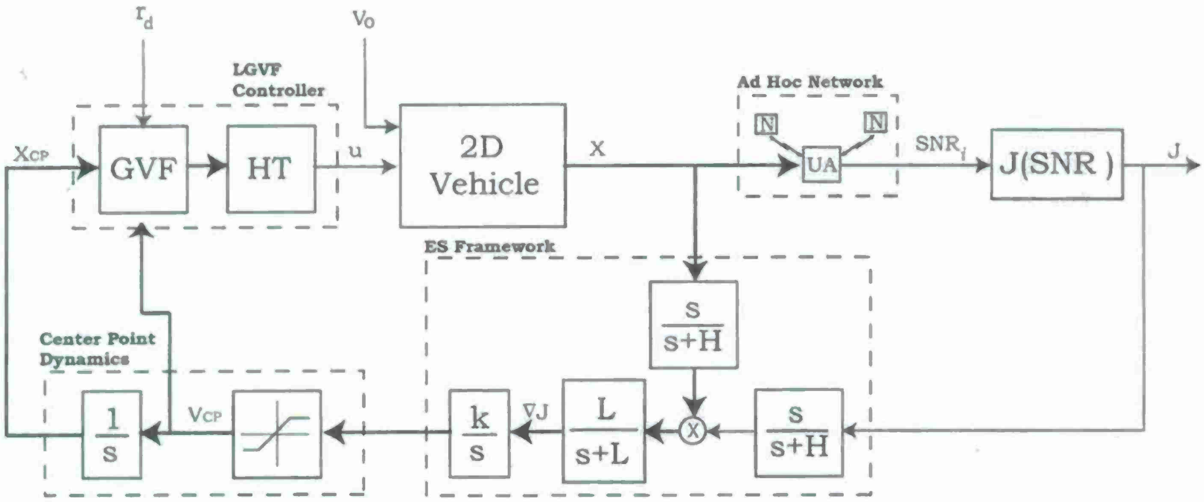

Figure 3. An extremum-seeking architecture for a linked network chain of mobile relay nodes in 2D. For a non-holonomic vehicle such as an unmanned aircraft, an orbit-tracking controller provides the dither signal needed to estimate the field gradient.

4. The extremum seeking control architecture was applied to electronic leashing (finding a single radio emitting source) and chaining (forming an optimal cascade relay network) in simulation and experiment. Simulation results (Fig. 4) verified the stability of the control approach for electronic chaining while experimental flight results were obtained to demonstrate leashing (Fig. 5) [J.1, T.1, C.2, J.6].

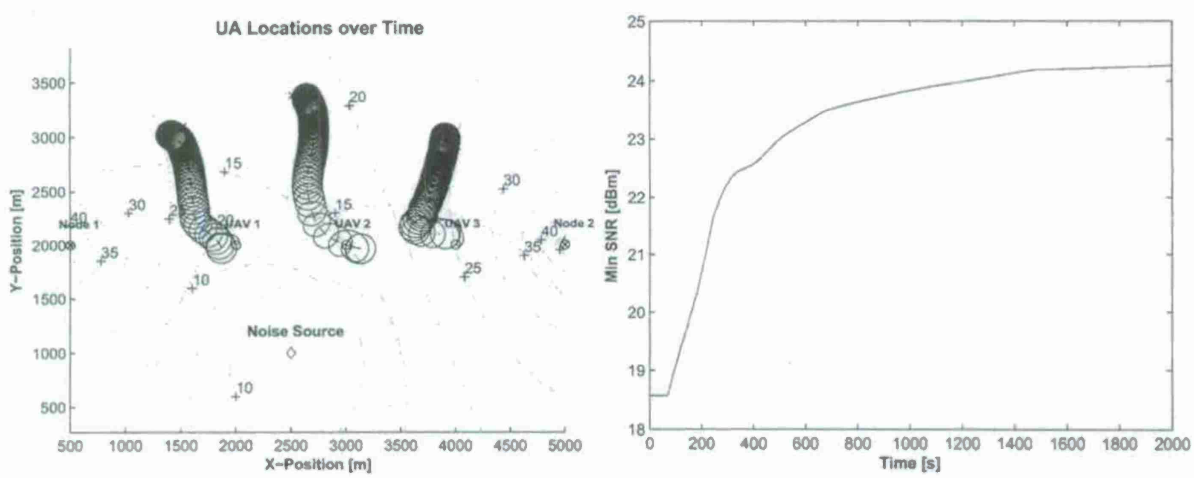

Figure 4. Simulation of three (3) UA relay nodes reacting to a localized noise source. (a) Motion of UAs within the environment also showing noise source location and the SNR contours of the two end nodes. (b) The minimum SNR value along the chain during the simulation.

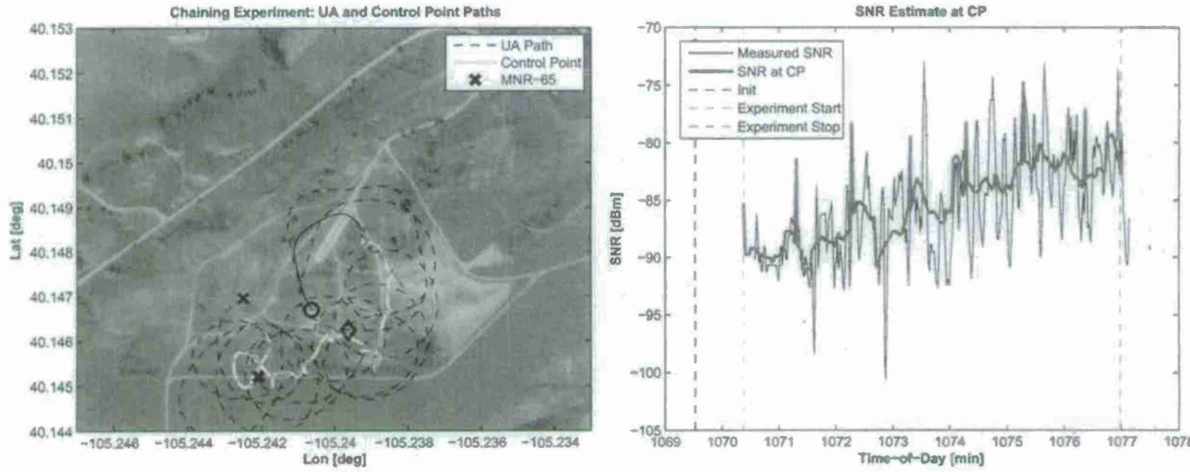

Figure 5. Experimental data from one UA leashed to a stationary ground nodes. (a) Motion of UA within the environment also showing RF source location. (b) Measured signal strength over time.

5. Ferrying route design using reinforcement learning has been developed and demonstrated in simulation (Fig. 6). It has been shown to exceed the performance of competing methods [T.2, C.4].

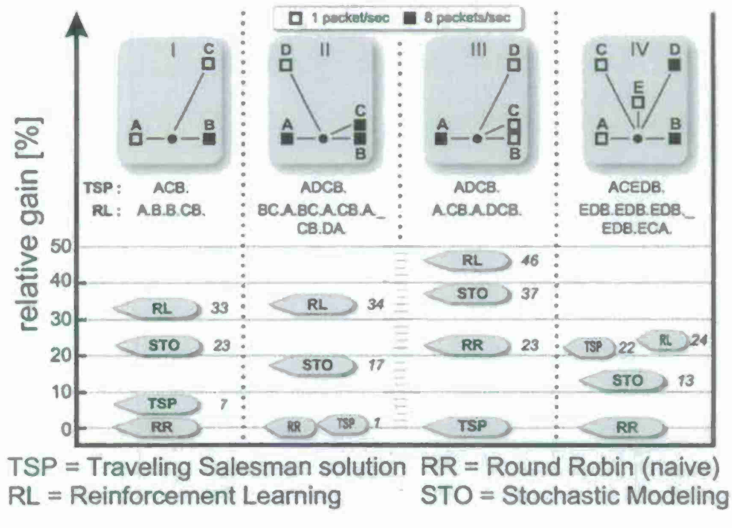

Figure 6. Performance of Reinforcement Learning path planning compared to competing methods on four different scenarios.

6. A DTN protocol has been developed to support data ferrying. In flights with unmanned aircraft (Fig. 7) it was shown to significantly increase the fraction of packets delivered compared to direct and relay communication [C.3].

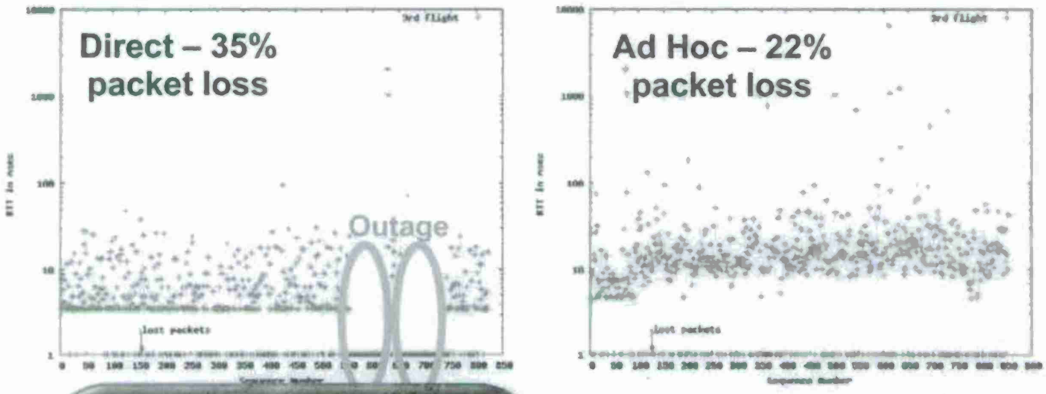

Figure 7. Comparison of different protocols' performances on actual unmanned aircraft flights. Ad hoc relaying using fixed nodes on the ground reduces packet loss from 35% to 22%. Adding a delay tolerant network protocol on top of the ad hoc network further reduces packet loss to 10%. The figure at right shows the experimental set-up on our test range.

5. Personnel Supported:

Eric W. Frew (PI)
Assistant Professor
Aerospace Engineering Sciences Department

Timothy X Brown
Associate Professor
Interdisciplinary Telecommunications Program
Electrical, Computer, and Energy Engineering Department

Cory Dixon
PhD candidate (Thesis Defense 5/09, expected graduation 8/09)
Aerospace Engineering Sciences

Dan Henkel
Graduate student (Received PhD 04/08)
Interdisciplinary Telecommunications Program

Andrew Jenkins
PhD Candidate
Electrical, Computer, and Energy Engineering Department

6. Publications:

Archival Journals

[J.1] Cory Dixon and Eric W. Frew. "Maintaining Optimal Communication Chains in Robotic Sensor Networks using Mobility Control." Invited to special issue of *Mobile Networks and Applications (MONET)*, 14(3):281-291 June 2009.

[J.2] Eric W. Frew and Timothy X. Brown. "Networking Issues for Small Unmanned Aircraft Systems." *Journal of Intelligent and Robotic Systems*, 54:21-37, March 2009.

[J.3] Eric W. Frew and Timothy X Brown, "Airborne Communication Networks for Small Unmanned Aircraft Systems." *Proceedings of the IEEE, Special Issue on Aviation Information Systems*, 96(12): 2008-2027, Dec. 2008.

[J.4] Eric W. Frew, Cory Dixon, Jack Elston, Brian Argrow, and Timothy X. Brown. "Networked Communication, Command, and Control of an Unmanned Aircraft System. " *AIAA Journal of Aerospace Computing, Information, and Communication*, 5(4):84–107, 2008.

[J.5] Cory Dixon and Eric W. Frew, "Decentralized Mobility Control to Optimize Capacity in Cascade Wireless Network Chains." *IEEE Transactions on Control System Technology*, 2008, under revision.

[J.6] Cory Dixon and Eric W. Frew, "Decentralized Multivariable Extremum Seeking for Nonholonomic Vehicles Acting as Communication Relays." *IEEE Transactions on Control System Technology*, in preparation.

Theses

[T.1] Cory Dixon. *Controlled Mobility of Unmanned Aircraft Chains to Optimize Capacity in Realistic Communication Environments*. PhD Thesis. University of Colorado, July 2009.

[T.2] Dan Henkel. *The Impact of Controlled-Mobility Helper Nodes on the Performance of Challenged Networks*. PhD Thesis. Technical University of Ilmenau, April 2009.

Book Chapters

[B.1] Cory Dixon and Eric W. Frew. "Decentralized Extremum-Seeking Control of Nonholonomic Vehicles to Form a Communication Chain." *Advances in Cooperative Control and Optimization*. Lecture Notes in Computer Science, Vol. 369, Michael J. Hirsch, Panos Pardalos, Robert Murphey, and Don Grundel, Eds. Springer-Verlag, Nov. 2007 ISBN: 978-3-540-74354-5.

Conference Proceedings

[C.1] Eric W. Frew and Timothy X. Brown. "Airborne Communication Networks for Small Unmanned Aircraft Systems." In *International Symposium on Unmanned Aerial Vehicles*, Orlando, FL, June 2008.

[C.2] Eric W. Frew, Cory Dixon, Jack Elston, and Maciej Stachura. "Active Sensing by Unmanned Aircraft Systems in Realistic Communication Environments." *IFAC Workshop on Networked Robotics,* Golden, CO, October 2009.

[C.3] D. Henkel, T. X Brown, "Delay-Tolerant Communication using Mobile Robotic Helper Nodes", *Proc. The First Workshop on Wireless Multihop Communications in Networked Robotics*, Berlin, Germany, Apr. 4, 2008.

[C.4] D. Henkel, T. X Brown, "Towards Autonomous Data Ferry Route Design through Reinforcement Learning", *Proc. Autonomic and Opportunistic Communications Workshop*, Los Angeles, Jun. 21, 2008, 6pp.(6 pages)

[C.5] Cory Dixon and Eric W. Frew. "Maintaining Optimal Communication Chains in Robotic Sensor Networks using Mobility Control." In *Proceedings of the First International Conference on Robot Communication and Coordination (Robocomm)*, Athens, Greece, October 2007.

[C.6] Cory Dixon and Eric W. Frew. "Cooperative Electronic Chaining Using Small Unmanned Aircraft". In *AIAA Infotech@Aerospace*, Rohnert Park, CA, May 2007.

[C.7] Cory Dixon and Eric W. Frew. "Decentralized Extremum-Seeking Control of Nonholonomic Vehicles to Form a Communication Chain." *Proceedings of 7th International Conference on Cooperative Control and Optimization*, Gainesville, FL, January 2007.

[C.8] A. Jenkins, D. Henkel, and T. X. Brown, "Sensor data collection through gateways in a highly mobile mesh network," in *IEEE Wireless Communications and Networking Conference*, Hong Kong, China, 2007, pp. 2786 – 2791.

[C.9] Y. Zhang, T. X Brown, "Aisle Routing for Mobile Ad Hoc Networks", in *Proc. IEEE Wireless Communications and Networking Conference* (WCNC), Las Vegas, Mar. 31-Apr. 3, 2008. 6pp. (6 pages)

[C.10] A. Jenkins, D. Henkel, T. X Brown, "Reliable Data Collection in Challenged Networks using Unmanned Aircraft", in *Proc. ACM MobiCom workshop on Challenged Networks (CHANTS)*, Montreal, Aug. 17 2007. 3pp. (3 pages)

[C.11] D. Henkel, T. X Brown, "Route Design for UA-based Data Ferries in Delay Tolerant Wireless Networks", *Proc. AIAA Infotech@Aerospace Conference*, May 7-10, 2007. 9pp. (9 pages)

[C.12] A. Jenkins, D. Henkel, T. X Brown, "Sensor Data Collection through Unmanned Aircraft Gateways", *Proc. AIAA Infotech@Aerospace Conference*, May 7-10, 2007. 8pp. (8 pages)

[C.13] D. Henkel, T. X Brown, "Optimizing the Use of Relays for Link Establishment in Wireless Networks", in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Hong Kong, March 2007. (6 pages 850 of 1721 accepted)

[C.14] A. Jenkins, D. Henkel, T. X Brown, "Sensor Data Collection Through Gateways in a Highly Mobile Mesh Network", in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Hong Kong, March 2007. (6 pages 850 of 1721 accepted)

[C.15] D. Henkel, C. Dixon, J. Elston, T. X Brown, "A Reliable Sensor Data Collection Network Using Unmanned Aircraft", in *Proc. Second International Workshop on Multi-hop Ad Hoc Networks: from theory to reality (REALMAN)*, Florence, May 26, 2006.

[C.16] T. X Brown, D. Henkel, "On Controlled Node Mobility in Delay-Tolerant Networks of Unmanned Aerial Vehicles", in *Proc. of International Symposium on Advanced Radio Technologies (ISART)*, Boulder, CO, March 7-9, 2006.

[C.17] Cory Dixon and Eric W. Frew, "Maintaining a Linked Network Chain Utilizing Decentralized Mobility Control", In *AIAA Guidance, Navigation and Control Conference and Exhibit*, AIAA, Keystone, CO, 21 - 24 Aug. 2006.

[C.18] Cory Dixon, Daniel Henkel, Eric W. Frew, and Timothy X. Brown, "Phase Transitions for Controlled Mobility in Wireless Ad hoc Networks", In *AIAA Guidance, Navigation, and Control Conference*, Keystone, CO, August 2006.

7. Interactions/Transitions:

a. Presentations:

[1] T. X Brown, "The role of controlled mobility in wireless networks," ECE Department at Colorado State University, Fort Collins, Feb. 19, 2007

[2] T. X Brown, "The Role of Communication in UAS in the Next 10 Years," First Community Symposium dedicated to Civilian Applications of Unmanned Aircraft Systems (CAUAS)}, Boulder, CO, Oct. 2, 2007.

[3] Eric W. Frew, "Networked Communication, Command, and Control (C3) of a Team of Unmanned Aircraft." Air Force Institute of Technology, Nov. 16, 2007.

[4] T. X Brown, "Controlled Mobility in Wireless Networks," Tsinghua U., Mar. 7, 2008.

[5] Eric W. Frew, "Planning and Control of Unmanned Aircraft Systems in Realistic Communication Environments." *Electrical Engineering Department Seminar*, University of New Mexico, Nov. 14, 2008.

[6] Eric W. Frew, "Planning and Control of Unmanned Aircraft Systems in Realistic Communication Environments." *Mechanical Engineering Department Seminar*, Tufts University, March 5, 2009.

[7] Eric W. Frew, "Planning and Control of Unmanned Aircraft Systems in Realistic Communication Environments." MIT, March 6, 2009.

[8] T. X Brown, "Wireless Networking for Disaster Management," Colorado School of Mines, April 28, 2009.

b. None

c. Transitions: This work continues to overlap with the AUGNet project at the University of Colorado funded by L3 Communication in conjunction with USAF Big Safari Special Group (BSSG). The work on delay tolerant networks (DTN) has also recently become part of an effort by NASA to incorporate robust communications into challenged networks. This is a project at CU and includes a test bed with DTN nodes at all the NASA centers and the International Space Station. Specific projects that leveraged aspects of this work include:

Title: Networked System Test Bed Integration and Test Phase 1
Source of Support: L3 Communications
Investigators: Tim Brown (PI), Brian Argrow, and Eric W. Frew
Total Award Amount and Period Covered: $343,462; 10/01/07 – 03/27/09

Title: Remote Management of a Heterogeneous UAV Team
Source of Support: Raytheon IIS
Investigators: Eric W. Frew (PI), Brian Argrow, and Dale Lawrence
Total Award Amount and Period Covered: $135,000; 7/1/06 – 10/31/07

Title: UAV Sensor Data Collection
Source of Support: L3 Communication
Investigators: Tim Brown (PI), Brian Argrow, and Eric W. Frew
Total Award Amount and Period Covered: $367,000; 09/22/05 – 09/30/07

8. New discoveries, inventions, or patent disclosures: None
9. Honors/Awards: None

An Integrated Framework for Controlled Mobility in Ad-hoc Networks
Grant Number: FA9550-06-1-0205 Eric W. Frew (PI) and Timothy X Brown
University of Colorado

The overall goal of this research project is to develop a framework for controlled mobility in ad-hoc networks that integrates data ferrying in sparse or delay tolerant networks with local decentralized control for improved real-time network flow. The original Statement of Work still holds.

We have completed objectives O1 - O5. Flight testing of the algorithms developed to meet these will be conducted in Summer 2008. Major accomplishments this past year include analysis of decentralized control for optimizing capacity of linear cascade network chains and designing data ferry routes using reinforcement learning algorithms that outperform standard Traveling Salesperson and stochastic programming approaches. Five archival publications have been generated (1 published, 2 accepted and 3 under review) through this effort. Aspects of this project continue to transition into work funded by L3 Communication and USAF Big Safari Special Group.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
An Integrated Framework for Controlled Mobility in Ad-hoc Networks

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-06-1-0205

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Eric Frew, Tim Brown

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Colorado

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR
875 N Randolph, Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-OSR-VA-TR-2012-0073

12. DISTRIBUTION/AVAILABILITY STATEMENT
Dist A

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The overall goal of the research proposed here is to develop a framework for controlled mobility in ad-hoc networks that integrates data ferrying in sparse or delay tolerant networks with local decentralized control for improved real-time network flow. Ferrying route design using reinforcement learning has been developed and demonstrated in simulation. It has been shown to exceed the performance of competing methods.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*